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Investigating the Relation between Level of Service and Volume-to-Capacity ratio at Signalized Intersections under Heterogeneous Traffic Condition

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Abstract

Among the various performance measures for assessing the operational condition of signalized intersection, both volume-to-capacity (*v/c*) ratio and control delay have gained importance universally. Even though delay is used as the service measure for arriving at the level of service (LOS) of signalized intersection, the practitioners use *v/c* ratio as the prime indicator of intersection performance. This study aims at understanding the significance of using the *v/c* ratio as an indicator of signalized intersection performance under Indian context. Previous studies and various highway capacity manuals have proposed a one-to-one relationship between delay and *v/c* ratio. The relationship has been revisited to find out whether there is a one-to-one correspondence. Further, an attempt was made to investigate the relationship between level of service and the *v/c* ratio at signalized intersection under heterogeneous traffic condition. The delay model proposed in the Indian Highway Capacity Manual (Indo-HCM) has been used for this. The results show that the delay distribution under different degrees of saturation are overlapping and it is difficult to arrive at *v/c* thresholds for each LOS category. i.e. there is no one-to-one correspondence between *v/c* ratio and delay values. Based on the study results, some approximate thresholds of *v/c* ratios are proposed for LOS of signalized intersections under heterogeneous traffic condition.

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Keywords: Level of service; Volume-to-capacity ratio; Perceived waiting time; Actual waiting time; User perception; Heterogeneous traffic; Signalized intersection; Indian Highway Capacity Manual

Introduction

Indian traffic is characterized by the presence of heterogeneous traffic and loose lane discipline (Tiwari et al., 2011). Despite having lane markings, most of the time lane discipline is not followed especially at signalized intersections.

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The United States Highway Capacity Manual (HCM) assumes homogeneous and lane based traffic for analysis. Due to these fundamental differences, the direct application of the models proposed in the manual to the prevailing heterogeneous traffic condition in India is questionable. For example, the control delay thresholds proposed by the universally accepted HCM 2010 ranges from less than 10 seconds to more than 80 seconds. As the users' have come to expect higher congestion, the tolerance to waiting time have increased. Waiting for more than one or two minutes is not an uncommon situation in India. Hence, the thresholds given in HCM 2010 do not adequately address the entire spectrum of the real world delay ranges in developing countries like India. Considering the need for a Highway Capacity Manual for India, Council of Scientific and Industrial Research-Central Road Research Institute (CSIR-CRRI) in coordination with the prominent academic institutes in the country has taken up a project named "Development of Indian Highway Capacity Manual (Indo-HCM)"(2013). A number of evaluation criteria are available for assessing the operational condition at signalized intersections. Some of these criteria are volume-to-capacity ratio (*v/c*), queue-storage ratio, control delay. The literature on the level of service (LOS) shows that mainly LOS of signalized intersections are defined over two variables-delay and *v/c* ratio ("Highway Capacity Manual," 2010, "Highway Capacity Manual," 2000, Transportation Research Circular 212, 1980; Kittelson, 2000; Kittelson and Roess, 2001; Zhang, 2004). In traffic engineering, traffic volume represents the traffic demand for a particular transport facility at a given point of time, while the capacity of that facility stands for the supply-side factor. Therefore, several studies have been attempted to use the *v/c* ratio as a service measure.

Even though the highway capacity manuals of various countries have proposed methodologies for arriving at the LOS, many researchers have pointed out that the actual LOS is not explicitly calculated or derived from the methodology provided. This may be because of the complex analytical delay models or maybe because of the tedious process of field delay calculation. Being easily understandable and less tedious to calculate (compared to delay estimation); practitioners use *v/c* ratio as the prime indicator of intersection performance. Hence, *v/c* ratio can be selected as an equally appropriate measure of effectiveness for the purposes of analysis and possibly a more convenient one, given that free-flow speed and capacity can be estimated, while known difficulties are involved in the accurate measurement of delay.

According to many researchers, the main drawback of considering delay as the sole service measure is that it can suggest an acceptable level of service when in reality certain lane groups (particularly those with lower volumes) are operating at an unacceptable LOS but are masked at the intersection level by the acceptable performance of higher-volume lane groups. According to Dowling (2007), "volume-to-capacity ratio is used to quickly determine if the facility has a sufficient number of lanes (sizing the facility) regardless of signal timing". For planning purposes, it may be more appropriate to consider the provision of adequate future capacity as related to geometric design features. Delay may be less of a concern, because it may be improved significantly through coordination of signals and improved signal design. Since 1985, the US HCM uses delay as the service measure at signalized intersection. Along with delay, US HCM 2010 considers *v/c* ratio as a performance measure for the evaluation of signalized intersection. The studies carried out at 336 intersection approaches forms the basis for the control delay LOS criteria (Pecheux et al., 2000). Control delay alone is used to characterize LOS for the entire intersection or an approach. Whereas, control delay and *v/c* ratio are used to characterize LOS for a lane group. The rationale behind the analogy is that delay is a measure of users' satisfaction with the facility whereas *v/c* ratio is a rational measure of how well the intersection is able to accommodate the demand. Whenever the *v/c* ratio is greater than or equal to one, irrespective of the delay value, the level of service falls to category F. Similarly, even if the *v/c* ratio is less than one, level of service falls to category F if the delay value is more than 80 seconds/vehicle.

Contrary to US HCM, the Canadian Capacity Guide (CCG) 2008 (Teply et al., 2008) for signalized intersection defines each LOS category in terms of certain ranges of *v/c* ratio. The line of reasoning adopted for doing so was that the degree of saturation determines the pattern of change in delay. The intersection performance deteriorates rapidly at degrees of saturation above 0.8 to 0.9. However, for the overall evaluation of the intersection, the manual recommends the use of both delay and *v/c* ratio. According to Akcelik (Akcelik, 1981, 1978), the degree of saturation can be used as a simple indicator of signalized intersection level of service. Figure 1 demonstrates the relationship between LOS and *v/c* ratio proposed by Akcelik and CCG 2008. For LOS D, the thresholds recommended by both the studies are same. As per CCG 2008, the first significant reduction of LOS occurs at v/c ratio of 0.6. Beyond 0.6, the relation between LOS and *v/c* ratio is linear. In case of relation proposed by Akcelik, the first significant reduction of LOS occurs at *v/c* ratio of 0.4. The relation between LOS and *v/c* ratio is not linear. In case of US HCM 2010, whenever the *v/c* ratio is more than 1, the LOS falls to category F irrespective of the delay value. As per Akcelik, LOS falls to category F when *v/c* is more than 0.95 whereas CCG considers congested condition when *v/c* is more than 1.

Indonesian HCM (1993) has defined level of performance (LOP) and LOS separately. The manual defines LOP as "the quantitative measure describing the operational conditions of a traffic facility as perceived by the highway authority (generally described in terms of capacity, degree of saturation, average speed, travel time, delay, queue probability, queue length, ratio of stopped vehicles)". LOS is defined as "the qualitative measure describing the operational conditions within a traffic stream and their perception by highway users (generally described in terms of speed, travel time, freedom to maneuver, traffic interruptions, comfort, convenience, and safety)". However, there was no information on how to address these factors into the LOS criteria.

In the literature, not much has been reported about how the LOS thresholds based on *v/c* ratio are arrived at. Many researchers like Akcelik, Zheng and Van Zuylen etc. found that it is difficult to arrive at *v/c* ranges corresponding to each LOS category. Akcelik (1978) stated that "the relationship between degree of saturation and level of service may be regarded as somewhat arbitrary and subjective and this is inevitable since level of service is a qualitative definition of operating conditions". According to Zheng and Van Zuylen (2010), "the delay distributions under different degrees of saturation are overlapping, which indicates that it is difficult to determine the traffic state for a given single-valued delay and vice versa".

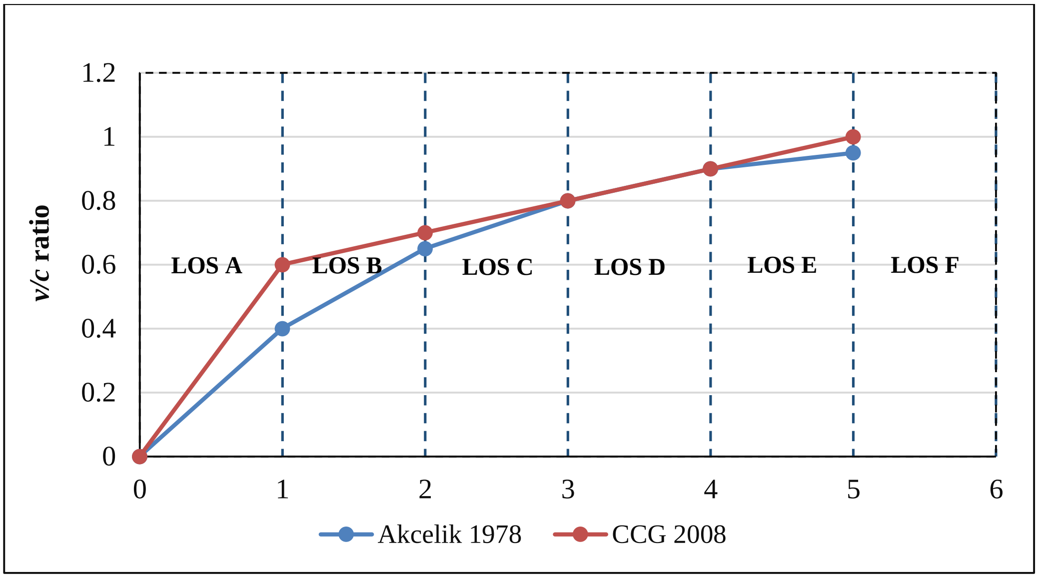

Fig. 1. Relationship between LOS and *v/c* ratio.

Layton (1996) stated that "although *v/c* affects delay, there are other parameters that more strongly affect it, such as the quality of progression, length of green phases, cycle lengths, and others". Thus, for any given *v/c* ratio, a range of delay values may result, and vice versa. Hence, there is a need to revisit the proposed relation by the various manuals to find out whether there exists a one-to-one correspondence. Also, due to the underlying difference in the traffic conditions like presence of heterogeneous traffic and non-lane discipline prevailing in developing countries like India, the delay and *v/c* thresholds proposed in other countries cannot be adopted. Hence, there is a need to investigate the relation between delay and *v/c* thresholds corresponding to each LOS category for Indian signalized intersections.

Data Collection

The data collected for the Indo-HCM project has been used for the present study. User perception survey and video-graphic data collected from fifteen signalized intersections from various cities of India forms the database for the present study. The study locations include New Delhi, Kolkata, Mumbai, Surat, Baroda, and Ahmedabad. The location details of the study intersections are given in Table 1. All the selected intersections are fixed time signals with either three-legged or four-legged. Some intersections included in the study are having very good flow characteristics with wide approaches, flared geometry at the stop-line, and exclusive left-turn lanes. Whereas, the traffic flow at some of the intersections are influenced by the pavement conditions, roadside activities and parking. Hence, this data represents the wide variation of traffic and geometric characteristics at the intersections prevailing in the Indian context. The geometric and traffic details of the study intersections are given in Table 2.

Table 1. Location details of the study intersections.

Intersection Identity	Name of Intersection	City	Coordinate
A	Aashirwad Chowk	New Delhi	28° 35' 47.9" N 77° 2' 59.9" E
B	Deepali Chowk	New Delhi	28° 41' 53.1" N 77° 7' 11.6" E
C	Depot Chowk	New Delhi	28° 35' 41.3" N 77° 4' 18.7" E
D	Firozshah-KG Marg Junction	New Delhi	28° 37' 22.1" N 77° 13' 31.5" E
E	NTPC Chowk	New Delhi	28° 36' 3.6" N 77° 22' 20.9" E
F	PTS Chowk	New Delhi	28° 31' 58.1" N 77° 11' 45.0" E
G	Stadium Chowk	New Delhi	28° 35' 23.6" N 77° 20' 9.5" E
H	Vardhaman Chowk	New Delhi	28° 35' 29.2" N 77° 3' 27.6" E
I	Vijay Char Rastha	Ahmedabad	23°02'34.1"N 72°32'56.01"E
J	GEV Circle	Vadodara	22°18'37.7"N 73°9'54.3"E
K	Rangila Park Intersection	Surat	21°10'29.9"N 72°48'18.9"E
L	IIT Bombay Main Gate Intersection	Mumbai	19° 7' 30.3" N 72° 54' 59.7" E
M	Shivaji Chowk	Mumbai	19° 4' 28.3" N 72° 59' 52.0" E
N	Kona Intersection	Kolkata	22°34'31.6"N 88°18'06.5"E
O	Rashbehari Intersection	Kolkata	22°31'02.4"N 88°21'08.6"E

Extensive user perception survey has been carried out at all the study intersections. Trained personnel's who are experts in speaking the local language along with English conducted the survey. The survey was carried out from 22nd September 2015 to 14th March 2016. A pilot survey was carried out to collect the perceived waiting time information as well as the users rating of signalized intersection. Survey was carried out when vehicles were stopped at the red signal. Results showed that the willingness of the users to respond was very less. Hence, it was decided to carry out the survey at locations near the intersections where the road users can respond comfortably. The exact survey locations include commercial buildings, workplaces, fuel stations and bus depots, around the intersection. Before interviewing, it was ensured that the respondent has traveled through the intersection concerned the very same day or the day before the interview.

Table 2. Geometric and traffic details of the study intersections.

Name of the intersection	Approach name	Location Details		Geometric Details						Signal and Traffic Details		
		Type (4/3 Legged)	**Area Type**	**Approach width (m)**	**No. of lanes**	**Service lane**	**Road markings**	**Stop line marking**	**Channelization**	**Exclusive Right Lane**	**Exclusive Right Phase**	**Free left Turn**
Ashirwad Chowk	Approach 1	4	Residential	10.5	3	No	Yes	Yes	Fully channelized	No	No	Yes
	Approach 2		Residential	10.6	3	No	Yes	Yes	Fully channelized	No	No	Yes
Deepali Chowk	Approach 1	4	Residential	11.83	3	No	Yes	Yes	Fully channelized	No	No	Yes
	Approach 2		Residential	11.5	3	No	Yes	Yes	Fully channelized	No	No	Yes
	Approach 3		Residential	10.18	3	No	Yes	Yes	Fully channelized	No	No	Yes
	Approach 4		Residential	8	2	No	Yes	Yes	Fully channelized	No	No	Yes
Depot Chowk	Approach 1	4	Residential/ Recreation	10.85	3	No	Yes	Yes	Fully channelized	No	No	Yes
	Approach 2		Residential/ Recreation	10.8	3	No	Yes	Yes	Fully channelized	No	No	Yes
	Approach 3		Residential/ Recreation	11.3	3	No	Yes	Yes	Fully channelized	No	No	Yes
	Approach 4		Residential/ Recreation	10.5	3	No	Yes	Yes	Fully channelized	No	No	Yes
KG Marg Firozshah	Approach 1	4	Residential	9	3	No	Yes	Yes	Fully channelized	No	No	Yes
	Approach 2		Residential	8.35	2	No	Yes	Yes	Fully channelized	No	No	Yes
	Approach 3		Residential	8.36	4	No	Yes	Yes	Fully channelized	No	No	Yes
	Approach 4		Residential	7.5	4	No	No	No	Fully channelized	No	No	Yes
NTPC Chowk	Approach 1	4	Industrial	11	3	No	Yes	Yes	Fully channelized	No	No	Yes
	Approach 2		Industrial	11.42	3	No	Yes	Yes	Fully channelized	No	No	Yes
PTS Chowk Mehrauli	Approach 1	3	CBD	12.6	3	No	No	No	Fully channelized	No	No	NA
	Approach 2		Residential	10.4	3	No	Yes	Yes	Fully channelized	No	No	Yes
	Approach 3		CBD	9.7	3	No	Yes	Yes	Fully channelized	No	No	Yes
Stadium Chowk	Approach 1	4	Recreation	10.6	4	No	Yes	Yes	Fully channelized	No	No	Yes
	Approach 2		Recreation	10.8	4	No	Yes	Yes	Fully channelized	No	No	Yes

Name of the intersection	Approach name	Location Details		Geometric Details						Signal and Traffic Details		
		Type (4/3 Legged)	Area Type	Approach width (m)	No. of lanes	Service lane	Road markings	Stop line marking	Channelization	Exclusive Right Lane	Exclusive Right Phase	Free left Turn
	Approach 3		Recreation/ Industrial	7.6	2	No	Yes	Yes	Fully channelized	No	No	Yes
	Approach 4		Recreation/ Industrial	9.5	3	No	Yes	Yes	Fully channelized	No	No	Yes
Vardhman Chowk	Approach 1	4	Residential	10	3	No	No	No	Fully channelized	No	No	Yes
	Approach 2		Residential	10.36	3	No	No	No	Fully channelized	No	No	Yes
Vijay Char Rastha	Approach 1	4	CBD	7	2	No	Yes	Yes	Fully channelized	No	No	Yes
	Approach 2		CBD	8.3	3	No	Yes	Yes	Fully channelized	No	No	Yes
	Approach 3		CBD	9.1	2	No	Yes	Yes	Fully channelized	No	No	Yes
	Approach 4		CBD	8	3	No	Yes	Yes	Fully channelized	No	No	Yes
GEV Circle	Approach 1	3	CBD	9	3	No	Yes	No	Fully channelized	No	No	Yes
	Approach 2		CBD	11	3	No	Yes	Yes	Fully channelized	No	No	Yes
	Approach 3		CBD	8	3	No	Yes	Yes	Fully channelized	No	No	Yes
Rangila Park	Approach 1	4	CBD	7	2	No	No	Yes	No	No	No	No
	Approach 2		CBD	6	2	No	No	No	No	No	No	No
	Approach 3		CBD	8	2	No	No	No	No	No	No	No
	Approach 4		CBD	5	2	No	No	No	No	No	No	No
IITB Main Gate	Approach 1	4	Others	18	4	Yes	No	No	No	No	Yes	Yes
	Approach 2		Others	18	4	Yes	No	No	No	No	Yes	Yes
Shivaji Chowk	Approach 1	4	CBD	7	2	No	Yes	Yes	Fully channelized	No	No	Yes
	Approach 2		CBD	7	2	No	Yes	Yes	Fully channelized	No	No	Yes
	Approach 3		CBD	10.4	2	No	Yes	Yes	Fully channelized	No	No	Yes
	Approach 4		CBD	9.3	2	No	Yes	Yes	Fully channelized	No	No	Yes
Kona Intersection	Approach 1	4	CBD	10.8	2	No	Yes	Yes	No	No	No	No
	Approach 2		CBD	9.1	2	No	Yes	Yes	No	No	No	Yes
Rashbehari Intersection	Approach 1	4	CBD	9	2	No	No	No	No	No	No	No
	Approach 2		CBD	10.1	2	No	No	No	No	No	No	No

A retrospective approach with category rating technique is used to obtain the perceived waiting time from the users. In category rating, the surveyor presents the temporal interval and the respondents locate the perceived waiting time in one of the 'm' ordered categories. As the users may not be able to understand the term 'delay' instead of it the term 'waiting time' was used. Finally, the users were requested to rate the LOS of the intersection in the standard A-F scale. A indicates "very good" and F indicates "very poor". The socio-economic information like age and gender and travel-related information like the purpose of the trip and frequency of the trip were also collected during the questionnaire survey. An overview of the questionnaire is shown in Figure 2. Only those samples with incomplete responses were discarded. Finally, a total of 8458 samples were obtained. Table 3 gives the details of the sample size collected from each of the study intersections.

Part A: Socio-economic information

1. Gender ☐ Male ☐ Female
2. Age ☐ 18-30 ☐ 30-55 ☐ above 55
3. Occupation ☐ Govt. employee ☐ Self-employed ☐ Student ☐ Others
4. Monthly Income (in thousands) ☐ <15 ☐ 15-40 ☐ 40-60 ☐ >60

Part B: Travel information

5. Purpose of trip ☐ Work ☐ Education ☐ Discretionary
6. Vehicle used for the trip ☐ Motorized two-wheeler ☐ Motorized three-wheeler ☐ Car ☐ Bus
7. How often you drive through this intersection ☐ Daily ☐ Occasionally
8. Approximate time of day at which you have crossed the intersection ____________
9. How much time normally you used to wait at the intersection?
☐<30 sec ☐30 sec-1min ☐ 1-2min ☐ 2-3min ☐ 3-4 min ☐ 4-8min ☐ 8-10min ☐>10min
10. Overall rating of this intersection as perceived by you: __________

A	B	C	D	E	F
Excellent	Very good	Good	Fair	Poor	Very poor

Fig. 2. User perception survey questionnaire format.

Table 3. Summary of the survey sample.

Intersection Identity	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Sample Size (number)	676	679	667	649	499	604	648	606	452	420	422	613	680	420	423
Sample Size (%)	8	8	8	8	6	7	8	7	5	5	5	7	8	5	5

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Video-graphic data has been collected for all the selected intersections for a duration of 3 hours for morning and evening peak hours. The camera location is fixed in such a way that stable and unobstructed view of each intersection approach including the stop line was achieved. At locations where it was not practical to collect the traffic data of all the approaches with a single camera, two cameras were used. The weather condition was sunny and warm during survey duration.

LOS Thresholds based on Perceived Waiting Time

As per the US HCM 2010, the delay threshold ranges from less than 10 seconds for LOS A to more than 80 seconds for LOS F. But these thresholds are not based on users' perception but based on the perception of transportation experts (Pecheux et al., 2000). Also, from the field, it was understood that the US HCM 2010 do not adequately address the entire spectrum of the real world delay ranges in developing countries like India. Waiting for more than one and a half minutes is not an uncommon situation in India. Hence, an attempt was made to revisit the relationship between LOS and delay, by proposing an approach that scales the LOS grade regimes by the users' perceived waiting time at the intersection.

The user perception survey directly gives the perceived waiting time at the signal by the users and the users LOS rating of the intersection. However, there are no means to track the actual waiting time of a particular user by the data collection methodology adopted in this study. Hence, from the video-graphic data collected at the intersections, the data on actual waiting time of each vehicle during the red signal was extracted. Initially, the actual waiting time data is extracted during the red time for 30 consecutive signal cycles. As the process is laborious and time consuming a t-test was carried out between the data set of thirty consecutive signal cycle and five consecutive signal cycle. The analysis result shows that there is no statistically significant difference between the mean of the two data sets (p-value = 0.214 and t-value = 0.79 at 5% significance level). Hence, for the further analysis, the actual waiting time data are extracted for 5 consecutive signal cycles of one of the approaches of every study intersection. The signal timing details of the study intersections are given in Table 4.

The actual waiting time can vary widely from 0% of the red time to more than 100% of the red time in heavily congested conditions or cycle failures. The mean actual waiting time at the subject intersections varied from 60% to 80% of the red time. Hence, on an average, the actual waiting time at an approach is assumed as 70% of the red time at that approach. As the users' perceived waiting time data, obtained through the questionnaire survey is ordered temporal intervals, the mean of each temporal interval is taken as the perceived waiting time. The perceived waiting time varies from 15 seconds to 540 seconds and the actual waiting time (i.e. 70% of red time) varies between 33.6-168 seconds for the study intersections. A simple linear regression was carried and the results show that the perceived waiting time is 1.8 times that of actual waiting time.

For each perceived LOS rating, the waiting time range corresponding to the maximum number of responses obtained is selected as the threshold for that particular LOS. For example, maximum number of respondents classified waiting time range '1-2 Min' as LOS C. Hence, the perceived waiting time threshold for LOS C is between 1 to 2 minutes. The perceived waiting time thresholds are converted to the actual waiting time in seconds based on the obtained relation. Table 5 gives the estimated LOS thresholds based on the perceived waiting time-actual waiting time relation. LOS thresholds obtained are almost twice the values suggested in US HCM 2010. It is worth noting that the Indian road users have a higher tolerance to waiting time. Highly mixed traffic and varying intersection geometries were found to be the cause behind the wide variation in the delay ranges from that specified in US HCM.

Table 4. Signal timing details of the study intersections.

Intersection	**Approach**	**Cycle time** (sec)	**Green time** (sec)	**Amber time** (sec)	**Red time** (sec)
Ashirwad Chowk	Approach 1	114	25	4	96
	Approach 2		30	4	79
Deepali Chowk	Approach 1	302	115	4	189
	Approach 2		107	4	191
	Approach 3		58	4	240
	Approach 4		65	4	233
Depot Chowk	Approach 1	140	30	4	106
	Approach 2		30	4	106
	Approach 3		30	4	106
	Approach 4		45	4	91
Firozshah-KG Marg Junction	Approach 1	130	60	3	67
	Approach 2		60	3	67
	Approach 3		40	3	87
	Approach 4		25	3	97
NTPC Chowk	Approach 1	187	60	4	124
	Approach 2		60	4	124
PTS Chowk	Approach 1	120	45	4	75
	Approach 2		45	4	75
	Approach 3		30	4	86
Stadium Chowk	Approach 1	127	30	3	94
	Approach 2		30	3	94
	Approach 3		30	3	94
	Approach 4		30	3	94
Vardhaman Chowk	Approach 1	115	25	3	96
	Approach 2		25	3	96
Vijay Char Rastha	Approach 1	180	45	3	135
	Approach 2		35	3	145
	Approach 3		25	3	155
	Approach 4		25	3	155
GEV Circle	Approach 1	150	45	3	102
	Approach 2		80	3	67
	Approach 3		25	3	122
Rangila Park Intersection	Approach 1	125	30	4	95
	Approach 2		30	4	95
	Approach 3		20	4	105
IIT Bombay Main Gate Intersection	Approach 1	170	95	3	75
	Approach 2		95	3	75
Shivaji Chowk	Approach 1	120	25	3	95
	Approach 2		25	3	95
	Approach 3		30	3	95
	Approach 4		30	3	95
Kona Intersection	Approach 1	144	85	4	50
	Approach 2		85	4	50
	Approach 3		65	4	85
Rashbehari Intersection	Approach 1	82	30	4	48
	Approach 2		30	4	48

Table 5. Proposed LOS thresholds for signalized intersection under heterogeneous traffic.

LOS	**Delay** (seconds)
A	≤ 20
B	20-40
C	40-65
D	65-95
E	95-130
F	≥ 130

Delay Model for Non-Lane Based Heterogeneous Traffic Condition

Among the various quantitative factors, delay is the most commonly used service measure for establishing the LOS of a signalized intersection as it relates directly to the experience of the drivers and its meaning is generally understood (Dion et al., 2004; Teply, 1989). It is considered as a surrogate measure of driver's discomfort, frustration and fuel consumption ("Highway Capacity Manual," 2010). Even though it is possible to measure the delay from the field, it is a tedious process. Hence, it is always convenient to have a predictive model for the estimation of delay.

For the present study, the delay model proposed in the Indo-HCM ("Indian Highway Capacity Manual," 2017) has been used. The delay model is given by Equation 1.

$$d = 0.9\, d_1 + d_2 \tag{1}$$

where, d is the average control delay in sec/PCU, d_1 is the average uniform delay in sec/PCU, d_2 is the average incremental delay in sec/PCU. The average uniform delay and average incremental delay for an isolated pre-timed signal are given by

$$d_1 = \frac{C}{2}\frac{\left(1-\frac{g}{C}\right)^2}{\left(1-\frac{g}{C}x\right)} \tag{2}$$

$$d_2 = 900T\left[(x-1)+\sqrt{(x-1)^2+\frac{4x}{cT}}\right] \tag{3}$$

where, T is the analysis period in hours, g is the effective green period in seconds, C is the cycle time in seconds, x is the degree of saturation in PCU/hour, c is the capacity in PCU/hour.

5. Relation between LOS and *v/c* Ratio

From the literature, it was understood that researchers have used either delay or *v/c* ratio or both as the performance measure at signalized intersection. Whether one parameter or the other is the most relevant is the subject of ongoing debate in the profession. As the practitioners use *v/c* ratio as the prime indicator of intersection performance, an attempt was made to investigate the relationship between LOS and *v/c* ratio for Indian intersections and thereby proposing the *v/c* thresholds for each LOS category. Initially, the *v/c* thresholds proposed by the Canadian Capacity Guide is revisited and thereafter the relationship between the LOS ranges proposed in the study based on the actual waiting time at the intersection and the *v/c* ratio is investigated.

5.1 Relation between LOS and v/c Ratio Based on CCG 2008

As the Canadian Capacity Guide for signalized intersection has provided the LOS thresholds based on *v/c* ratio, an attempt was made to revisit the relationship to ensure that there exists a one-to-one correspondence between LOS and *v/c* ratio as proposed in the manual. As per CCG 2008, a cycle length of 100 seconds is typical and hence for the analysis cycle time was assumed as 100 seconds. Even though *v/c* ratio affects delay, there are other parameters like green time and cycle time, which strongly affects delay. Hence, to investigate the relationship of *v/c* ratio and LOS, the delay values are calculated for different *v/c* and g/C (green ratio) ratios. g/C ratio considered ranges from 0.3 to 0.7. For each g/C ratio, delay has been calculated for *v/c* ratio ranging from 0.05 to 1.3. The manual assumes a saturation flow value of 1800 PCU/hour/lane in metropolitan area with good pavement surface and weather condition. For delay calculation, the model proposed by the manual has been used and the same is given by Equation 4.

$$d = d_1 PF + d_2 + d_3 \tag{4}$$

$$d_1 = 0.50\, C \frac{\left(1 - \frac{g}{C}\right)^2}{\left(1 - \frac{g}{C} x\right)} \tag{5}$$

$$d_2 = 15T \left\{ (x-1) + \sqrt{(x-1)^2 + \frac{240\, x}{cT}} \right\} \tag{6}$$

where, d is the average control delay in sec/veh, $d_1$is the average uniform delay per vehicle, d_2 is the average incremental delay per vehicle, PF is the progression adjustment factor, T is the analysis period in minutes and all other variables are previously defined.

The progression adjustment factor was assumed as 1.0. Analysis period was considered as 15 minutes. Table 6 gives the control delay values for various *v/c* and g/C ratio. It can be noted that, for a particular g/C ratio, as the *v/c* ratio increases the control delay estimates increases. This indicates that the *v/c* ratio strongly determines the pattern of change in delay. On the other hand, for a particular *v/c* ratio, the delay values go on decreasing as the g/C ratio increases. A drastic increase in delay can be observed above *v/c* ratio of 0.8. The colour code indicates the various LOS categories. This would be helpful to understand how the LOS shifts from one category to the other for different values of *v/c* and g/C ratio.

From the analysis results, it was found that the delay distribution under different degrees of saturation is overlapping. For example, for g/C ratio of 0.7, the LOS falls to category A for a range of *v/c* ratio from 0.05 to 0.65. Whereas for g/C ratio of 0.3, for the given set of input data, the above range of *v/c* ratio indicates LOS C. Also, for the given input data, LOS falls to category F only when the *v/c* ratio is more than 1.05. From the results, it is clear that for a particular LOS a wide range of *v/c* ratios exists. So it can be inferred that it is very difficult to arrive at the *v/c* ranges corresponding to each LOS category as proposed in the Canadian Capacity Guide.

Table 6. Variation of control delay with respect to *v/c* and *g/C* based on CCG.

Delay		***g/C***								
		0.3	**0.35**	**0.4**	**0.45**	**0.5**	**0.55**	**0.6**	**0.65**	**0.7**
v/c	**0.05**	25.0	21.6	18.4	15.5	12.9	10.5	8.3	6.4	4.7
	0.1	25.4	22.0	18.9	16.0	13.3	10.8	8.6	6.6	4.9
	0.15	25.9	22.5	19.4	16.4	13.7	11.2	8.9	6.9	5.2
	0.2	26.5	23.1	19.9	16.9	14.1	11.6	9.3	7.2	5.4
	0.25	27.0	23.6	20.4	17.4	14.6	12.0	9.7	7.6	5.7
	0.3	27.6	24.2	21.0	18.0	15.1	12.5	10.1	7.9	6.0
	0.35	28.3	24.8	21.6	18.5	15.7	13.0	10.6	8.3	6.3
	0.4	28.9	25.5	22.3	19.2	16.3	13.6	11.1	8.8	6.7
	0.45	29.7	26.2	23.0	19.9	16.9	14.2	11.6	9.3	7.2
	0.5	30.5	27.0	23.7	20.6	17.6	14.9	12.3	9.8	7.6
	0.55	31.4	27.9	24.6	21.4	18.4	15.6	13.0	10.5	8.2
	0.6	32.3	28.9	25.5	22.4	19.3	16.5	13.7	11.2	8.8
	0.65	33.5	30.0	26.6	23.4	20.3	17.4	14.6	12.0	9.6
	0.7	34.8	31.2	27.9	24.6	21.4	18.6	15.7	13.0	10.5
	0.75	36.4	32.8	29.3	26.1	22.8	19.9	17.0	14.2	11.6
	0.8	38.5	34.7	31.2	27.9	24.5	21.6	18.6	15.7	13.0
	0.85	41.3	37.4	33.7	30.3	26.7	23.8	20.8	17.8	14.9
	0.9	45.4	41.3	37.4	33.8	30.1	27.1	23.9	20.9	17.9
	0.95	52.0	47.6	43.5	39.7	35.6	32.7	29.3	26.1	23.0
	1	62.4	57.9	53.7	49.9	45.6	42.7	39.4	36.1	32.9
	1.05	76.5	72.1	68.0	64.3	60.2	57.3	54.1	50.9	47.8
	1.1	94.0	89.8	86.0	82.5	78.7	75.9	72.8	69.8	66.8
	1.15	113.5	109.6	106.0	102.7	99.1	96.4	93.4	90.5	87.6
	1.2	134.1	130.4	127.0	123.7	120.4	117.7	114.7	111.9	109.1
	1.25	155.3	151.7	148.4	145.3	142.1	139.4	136.5	133.7	131.0
	1.3	176.9	173.4	170.2	167.2	164.0	161.3	158.5	155.8	153.0

Note:	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F

5.2 Relation between LOS and v/c Ratio for Signalized Intersection under Heterogeneous Traffic Condition

To investigate the relationship between LOS and *v/c* ratio for signalized intersection under heterogeneous traffic condition, the same hypothetical data considered above has been used. The differences were in the saturation flow and the delay model considered. The saturated flow is calculated using the Saturation Flow Model proposed in the Indo-HCM. The unit base saturation flow is given by Equation 7.

$$USF_0 = \begin{cases} 630, w < 7\ m \\ 1140 - 60w, 7\ m < w < 10.5\ m \\ 500, w > 10.5\ m \end{cases} \quad (7)$$

where, USF_0 is the unit base saturation flow rate (PCU/hour/m) and w is the width of the approach (m).

The unit base saturation flow rate is adjusted for the various adjustment factor to obtain the prevailing saturation flow. Equation 8 gives the saturation flow.

$$SF = w \times USF_0 \times f_{bb} \times f_{br} \times f_{is} \quad (8)$$

where, SF is the prevailing saturation flow (PCU/hour), w is the width of the approach (m), USF_0 is the unit base saturation flow rate (PCU/hour/m), f_{bb} is the adjustment factor for bus blockage due to kerb side bus stop, f_{br} is the adjustment factor for blockage of through vehicles by standing right turning vehicles waiting for their turn, f_{is} is the adjustment factor for the initial surge of vehicles due to approach flare and anticipation effect.

It is assumed that the data considered is from a base intersection with no initial surge of vehicles, no bus blockage and no blockage of the through vehicles by the standing right-turning vehicle. Hence, the saturation flow will be equal to the product between width of the approach and the unit base saturation flow rate. The width of the approach was assumed as 7 meters. Delay values are calculated using the delay model proposed in the Indo-HCM (Equation 1). For investigating the relation between LOS and *v/c* ratio, the LOS ranges arrived based on the actual delay at signalized intersection (given in Table 5) has been used. Table 7 gives the variation of control delay values for various *v/c* and g/C ratio for signalized intersections under heterogeneous traffic condition.

Similar to earlier results, it was found that the delay distribution under different degrees of saturation is overlapping. For example, for g/C ratio of 0.7, the LOS falls to category A for a range of *v/c* ratio from 0.05 to 0.90. Whereas for g/C ratio of 0.3, for the given set of input data, the above range of *v/c* ratio indicates LOS B and LOS C. As the control delay depends on many other factors in addition to *v/c* ratio, it was found that there is no one-to-one correspondence between the control delay ranges and *v/c* ratio values. Moreover, it is to be reminded that the LOS ranges prescribed are arrived at based on users' perceived versus actual waiting time relation at signalized intersection. Therefore, it is even more difficult to establish any correspondence between LOS ranges of control delay and *v/c* ratio values. However, considering that *v/c* ratio would be a more convenient and helpful measure of effectiveness for the practitioners for the purpose of operational analysis, approximate ranges of *v/c* ratio are provided as a rough guide in working out the approximate LOS of a signalized intersection. Table 8 gives the approximate *v/c* ratio thresholds recommended for various LOS categories.

Table 7. Variation of control delay with respect to *v/c* and *g/C* based on the Indo-HCM delay model.

Delay		g/C								
		0.3	**0.35**	**0.4**	**0.45**	**0.5**	**0.55**	**0.6**	**0.65**	**0.7**
v/c	**0.05**	22.4	19.4	16.6	14.0	11.6	9.4	7.5	5.7	4.2
	0.1	22.9	19.8	17.0	14.3	11.9	9.7	7.7	6.0	4.4
	0.15	23.3	20.2	17.4	14.7	12.3	10.0	8.0	6.2	4.6
	0.2	23.8	20.7	17.8	15.2	12.7	10.4	8.3	6.5	4.8
	0.25	24.2	21.2	18.3	15.6	13.1	10.8	8.7	6.8	5.1
	0.3	24.7	21.7	18.8	16.1	13.5	11.2	9.0	7.1	5.3
	0.35	25.3	22.2	19.3	16.6	14.0	11.6	9.4	7.4	5.6
	0.4	25.8	22.8	19.9	17.1	14.5	12.1	9.9	7.8	6.0
	0.45	26.5	23.4	20.5	17.7	15.1	12.6	10.3	8.2	6.3
	0.5	27.1	24.1	21.1	18.4	15.7	13.2	10.9	8.7	6.7
	0.55	27.9	24.8	21.9	19.1	16.4	13.9	11.5	9.2	7.2
	0.6	28.7	25.6	22.6	19.8	17.1	14.6	12.1	9.9	7.7
	0.65	29.6	26.5	23.5	20.7	18.0	15.4	12.9	10.6	8.4
	0.7	30.6	27.5	24.6	21.7	19.0	16.3	13.8	11.4	9.1
	0.75	31.9	28.8	25.8	22.9	20.1	17.4	14.8	12.4	10.0
	0.8	33.5	30.3	27.3	24.3	21.5	18.8	16.2	13.6	11.2
	0.85	35.8	32.4	29.3	26.3	23.4	20.6	17.9	15.3	12.8
	0.9	39.1	35.6	32.3	29.1	26.2	23.3	20.5	17.8	15.1
	0.95	44.8	41.0	37.4	34.1	31.0	27.9	25.0	22.2	19.4
	1	54.6	50.7	47.0	43.6	40.4	37.3	34.4	31.5	28.7
	1.05	69.0	65.2	61.7	58.4	55.3	52.3	49.4	46.7	43.9
	1.1	87.1	83.6	80.3	77.2	74.3	71.5	68.8	66.1	63.5
	1.15	107.1	103.8	100.8	97.9	95.1	92.4	89.8	87.2	84.7
	1.2	128.2	125.0	122.1	119.3	116.6	114.0	111.4	108.9	106.5
	1.25	149.7	146.6	143.8	141.1	138.5	135.9	133.4	130.9	128.5
	1.3	171.5	168.5	165.8	163.1	160.5	158.0	155.5	153.1	150.7

Note:	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F

Table 8 Approximate *v/c* ratio for various LOS

Level of Service (LOS)	**Volume-to-Capacity Ratio (*v/c*)**
A	<0.60
B	0.60-0.85
C	0.85-0.95
D	0.95-1.05*
E	1.05-1.10*
F	>1.10*

**This needs to be interpreted as demand-capacity ratio*

Conclusions

Being easily understandable and less tedious to calculate, compared to the delay estimation practitioners use *v/c* ratio as the prime indicator of intersection performance. Previous studies and various highway capacity manuals have proposed a one-to-one relationship between the LOS and *v/c* ratio. An attempt was made to revisit the relationship between LOS and *v/c* ratio proposed in the Canadian Capacity Guide for signalized intersection. The relationship was revisited to find out whether there is one-to-one correspondence. Further investigation was carried out between *v/c* ratio and the LOS proposed in this study based on the actual waiting time at the signalized intersection and approximate *v/c* ranges were proposed for each LOS category.

The review of the significance of using *v/c* ratio as an indicator of intersection performance revealed that it could be selected as an equally appropriate measure of effectiveness for the purposes of LOS analysis. Compared to the known difficulty involved in the accurate measurement of delay, using *v/c* ratio as a rough indicator of intersection performance is more convenient. A revisit on the relation proposed in the Canadian Capacity Guide for signalized intersections shows that for a particular LOS a wide range of *v/c* ratios exists. From the analysis results, it was found that the delay distribution under different degrees of saturation is overlapping. Therefore, it can be inferred that it is very difficult to arrive at the *v/c* ranges corresponding to each LOS category as proposed in the Canadian Capacity Guide. Investigation on the relation between *v/c* ratio and the LOS for Indian intersections revealed that there is no one-to-one correspondence.

The greatest limitation of the present study is perhaps the lack of methodology to track the same users' perceived and actual waiting time. Instead of approximating the actual waiting time as some percentage of red time of that approach, the waiting time data may be simulated based on the distribution of actual waiting time at the intersection. In spite of this limitation, the approximate *v/c* ratio proposed for each LOS category can be used as a rough guide for the practitioners while evaluating the operational condition at the signalized intersection in India. The LOS thresholds obtained through this study has been recommended for the Indian Highway Capacity Manual.

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